



# Refractory Complex Concentrated Alloys (RCCAs)

ARPA-E Workshop  
20,21 November 2019

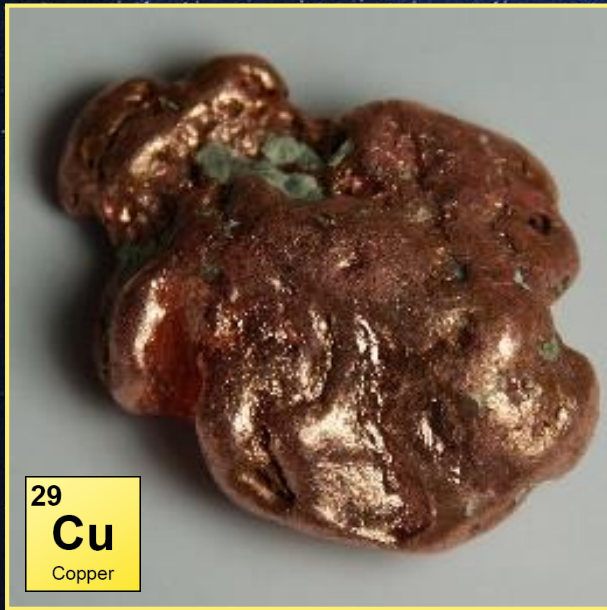
Dr. D.B. Miracle and Dr. O.N. Senkov  
Air Force Research Laboratory  
Materials and Manufacturing Directorate, Dayton, OH USA

# The history of metallic alloys

## Stone Age

## Bronze Age

## Iron Age



29  
**Cu**  
Copper



29  
**Cu**  
Copper

50  
**Sn**  
Tin



26  
**Fe**  
Iron

6  
**C**  
Carbon

13  
**Al**  
Aluminum

27  
**Co**  
Cobalt

12  
**Mg**  
Magnesium

42  
**Mo**  
Molybdenum

41  
**Nb**  
Niobium

28  
**Ni**  
Nickel

22  
**Ti**  
Titanium

30  
**Zn**  
Zinc

29  
**Cu**  
Copper

82  
**Pb**  
Lead

79  
**Au**  
Gold

47  
**Ag**  
Silver

50  
**Sn**  
Tin

80  
**Hg**  
Mercury

26  
**Fe**  
Iron

-9000 -8000 -7000 -6000 -5000 -4000 -3000 -2000 -1000 0 1000 2000

# Two Big Ideas

**“...to investigate the unexplored central region of multicomponent alloy phase space.”**

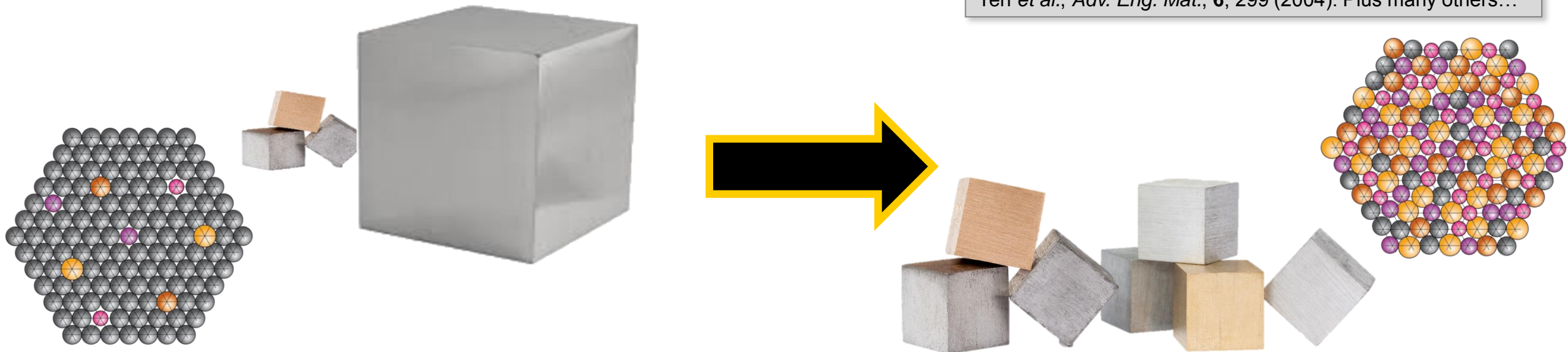
Cantor *et al.*, *Mat. Sci. Eng. A*, 375-377, 213 (2004).

- Vast opportunity to discover new alloys of scientific and practical benefit

**Favor solid solution over intermetallic phases thru configurational entropy**

- Vary entropy thru the number and concentrations of principal elements ( $N \geq 5$ )

Yeh *et al.*, *Adv. Eng. Mat.*, 6, 299 (2004). Plus many others...



**Both ideas focus on concentrated, multi-component alloys bases**

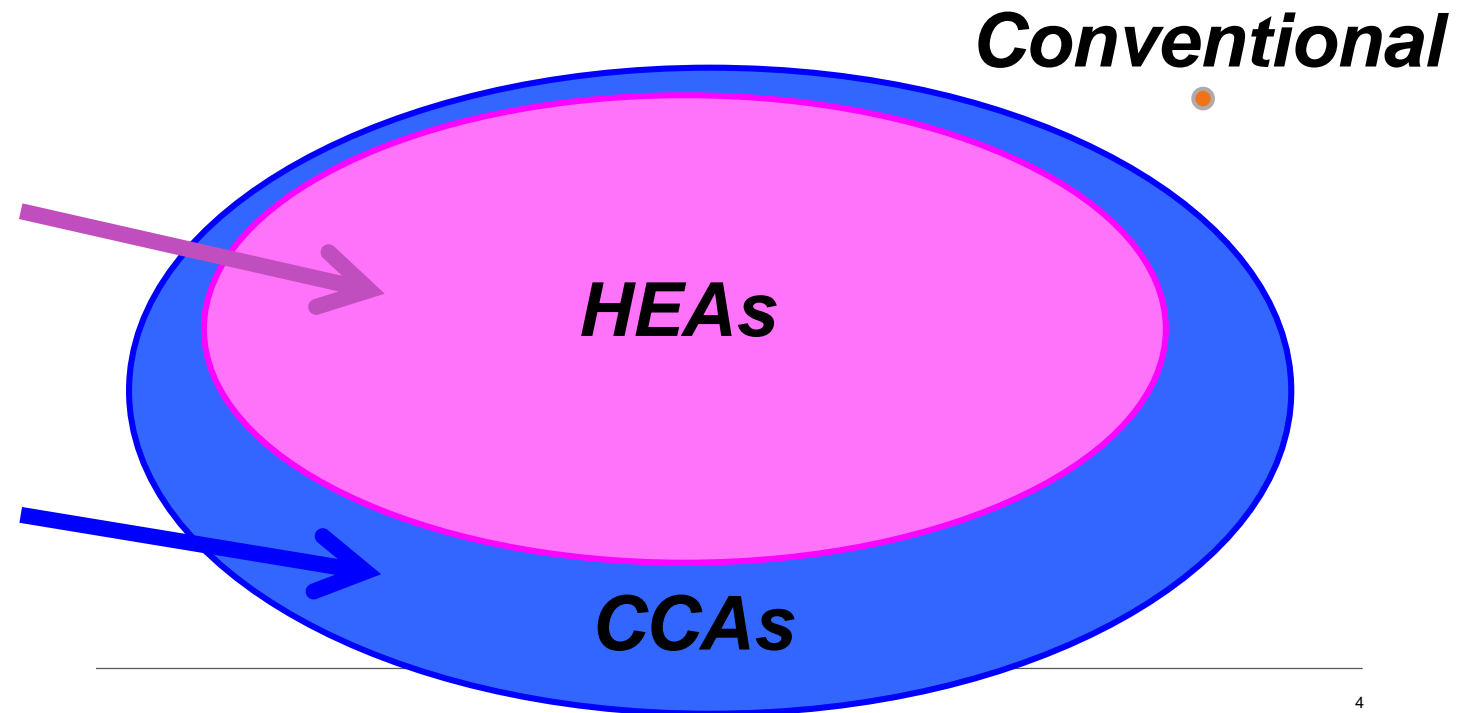
# HEAs and Complex, Concentrated Alloys (CCAs)

Attractive properties are found in alloys with  $N < 5$ , with concentrations  $>35\%$  and in microstructures with more than a single solid solution phase

Terms such as CCAs and multi-principal element alloys (MPEAs) further expand the possibilities

- *5 or more elements*
- *Nominally single-phase*
- *High configurational entropy*

- *May have  $<5$  elements*
- *Can have  $>35\%$  of elements*
- *Can have multiple phases*
- *Entropy doesn't matter*





High temperature metals remain a high impact,  
long-sought, unsatisfied challenge

*“ . . . but metal is in the heart of that machine. In all your machines, wherever you use fire and heat to make things move, there is metal.”*

Orson Scott Card, from “Speaker for the Dead” (1986)

# PERIODIC TABLE OF THE ELEMENTS

1 <b>H</b> Hydrogen 1.008																	2 <b>He</b> Helium 4.003	
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012																	10 <b>Ne</b> Neon 20.180
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305																	18 <b>Ar</b> Argon 39.948
19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.942	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.933	27 <b>Co</b> Cobalt 58.933	28 <b>Ni</b> Nickel 58.693	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.732	32 <b>Ge</b> Germanium 72.61	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.972	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 84.80	
37 <b>Rb</b> Rubidium 84.468	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.906	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.906	42 <b>Mo</b> Molybdenum 95.95	43 <b>Tc</b> Technetium 98.907	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.904	54 <b>Xe</b> Xenon 131.29	
55 <b>Cs</b> Cesium 132.905	56 <b>Ba</b> Barium 137.327	57-71	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.948	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.967	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.980	84 <b>Po</b> Polonium [208.982]	85 <b>At</b> Astatine 209.987	86 <b>Rn</b> Radon 222.018	
87 <b>Fr</b> Francium 223.020	88 <b>Ra</b> Radium 226.025	89-103	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [269]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>Fl</b> Flerovium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Lv</b> Livermorium [298]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown	
		57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.115	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.913	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.966	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.930	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967		
		89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium 244.064	95 <b>Am</b> Americium 243.061	96 <b>Cm</b> Curium 247.070	97 <b>Bk</b> Berkelium 247.070	98 <b>Cf</b> Californium 251.08	99 <b>Es</b> Einsteinium 252.083	100 <b>Fm</b> Fermium 257.10	101 <b>Mn</b> Mendelevium 258.10	102 <b>Lr</b> Lawrencium 260.10			

Intermetallics 18 (2010) 1758–1765

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Intermetallics

journal homepage: [www.elsevier.com/locate/intermet](http://www.elsevier.com/locate/intermet)



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Refractory high-entropy alloys

O.N. Senkov<sup>a,b,\*</sup>, G.B. Wilks<sup>a,c</sup>, D.B. Miracle<sup>a</sup>, C.P. Chuang<sup>d</sup>, P.K. Liaw<sup>d</sup>

# Common RCCAs and principal element combinations

Common 3 principal elements are (Nb,Ti,Zr), (Mo,Nb,Ti), (Nb,Ti,V)

Common 4 principal elements are (Mo,Nb,Ti,Zr), (Mo,Nb,Ti,V), (Nb,Ti,V,Zr)

The most common RCCAs are  
**HfNbTaTiZr, MoNbTaW, MoNbTaVW,  
 NbTiVZr and  $AlMo_{0.5}NbTa_{0.5}TiZr$**

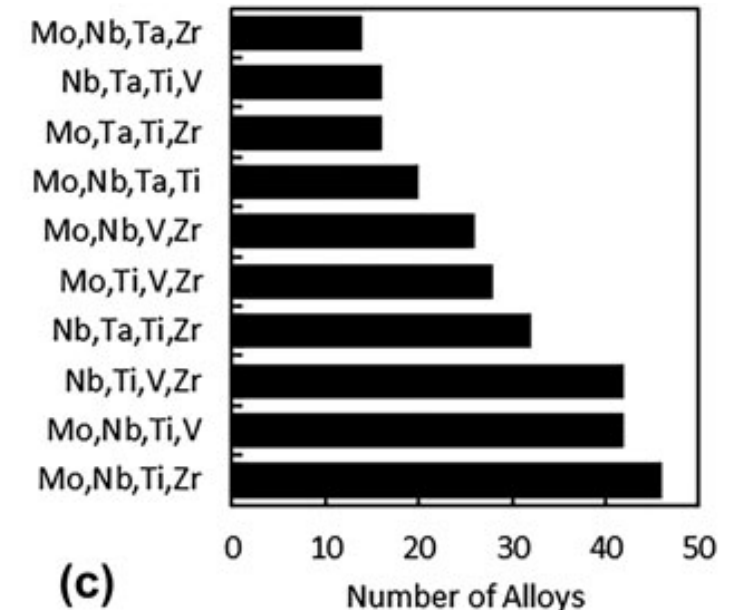
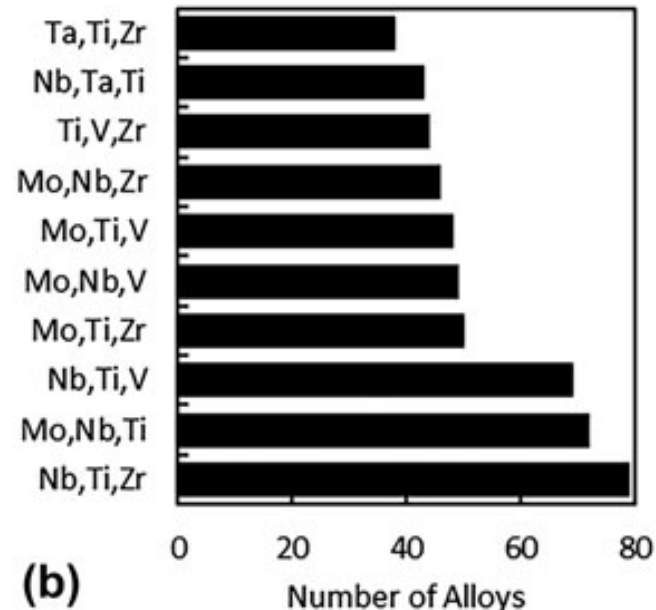
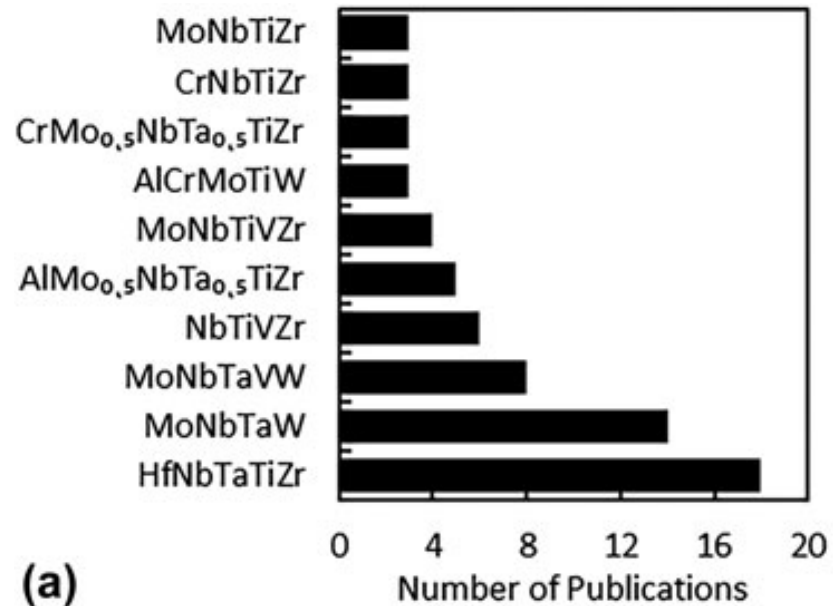
## INVITED REVIEW

*This section of Journal of Materials Research is reserved for papers that are reviews of literature in a given area.*

### Development and exploration of refractory high entropy alloys—A review

Oleg N. Senkov,<sup>a)</sup> Daniel B. Miracle,<sup>b)</sup> and Kevin J. Chaput  
 Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson AFB, Ohio 45433, USA

Jean-Philippe Couzinie  
 Université Paris Est, ICMPE (UMR 7182) CNRS-UPEC, 2-8 rue Henri Dunant, F-94320, Thiais F-94320, France



# Number and types of RCCA phases

## 1-phase BCC microstructures comprise 54% of RCCAs

- Most (57) contain only elements from subgroups IV-VI, but 24 contain Al, which stabilizes BCC structure in Hf, Ti and Zr

## 2-phase microstructures give 39% of RCCAs

- The matrix phase is BCC (48 alloys), B2 (8 alloys) or FCC (3 alloys)

## 3- and 4-phase alloys give 7% of RCCAs

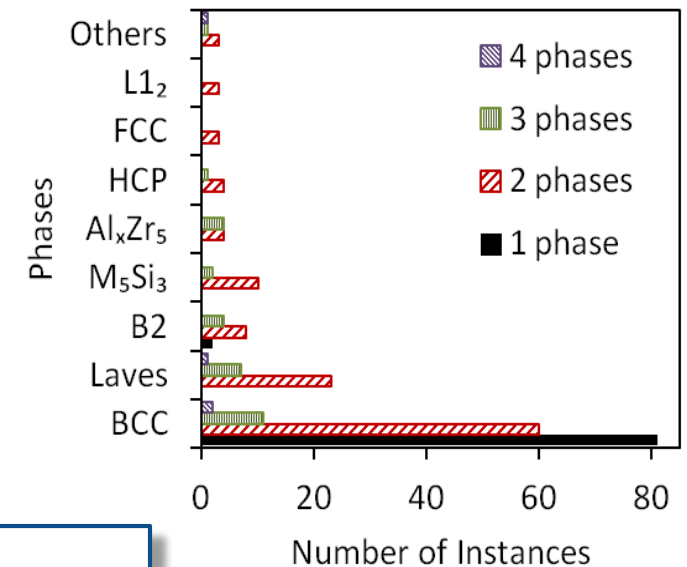
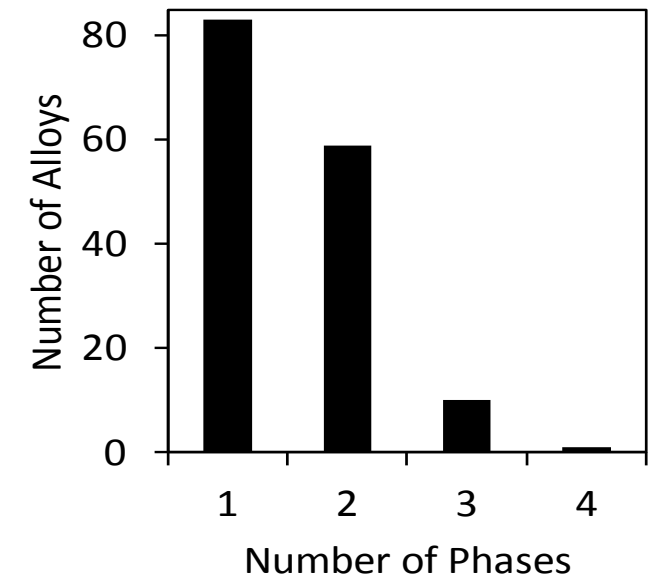
## Disordered BCC is the most common phase

## Laves (C14 or C15) is the 2<sup>nd</sup> most common

- Laves is always associated with Cr, Mo and Zr, and/or a combination of Al, V and Zr

## B2 often gives an RCCA ‘superalloy’ microstructure

- The main elements are Al, Nb, Ta and Zr



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# HEA Property Comparison

***RHEAs offer potential for improved high temperature strength and specific strength relative to superalloys and conventional refractory alloys***

INVITED REVIEW

This

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Full length article

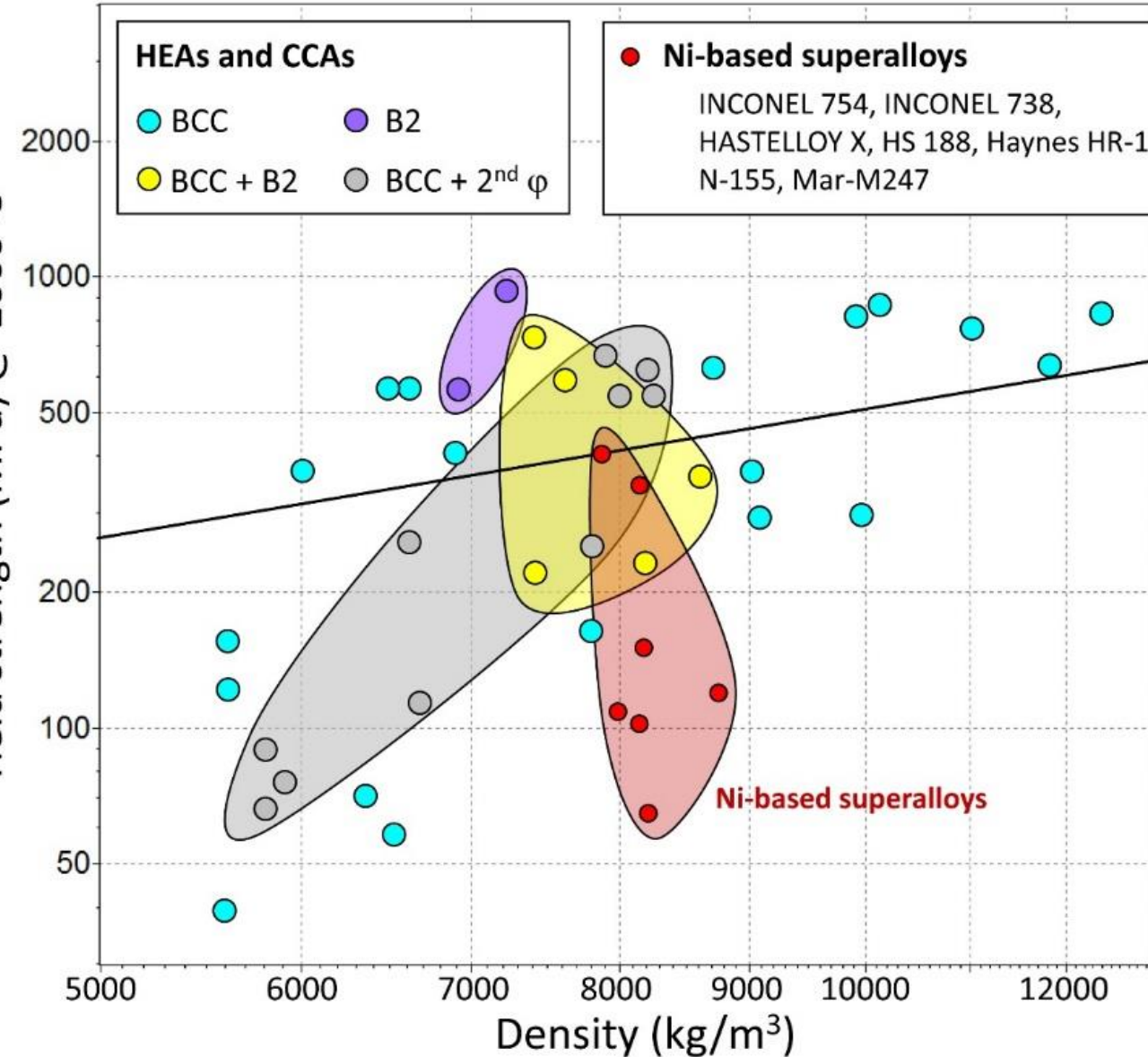
Mapping the world of complex concentrated alloys

Stéphane Gorsse <sup>a, b, c, \*</sup>, Daniel B. Miracle <sup>d</sup>, Oleg N. Senkov <sup>d</sup>

*Diao, Feng, Dahmen, Liaw, COSSMS, 21 (2017) 252*

Yield strength (MPa)

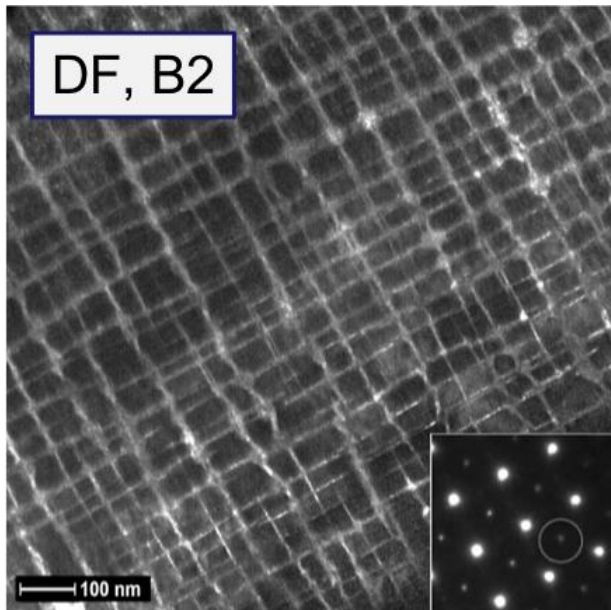
Yield strength (MPa) @ 1000°C



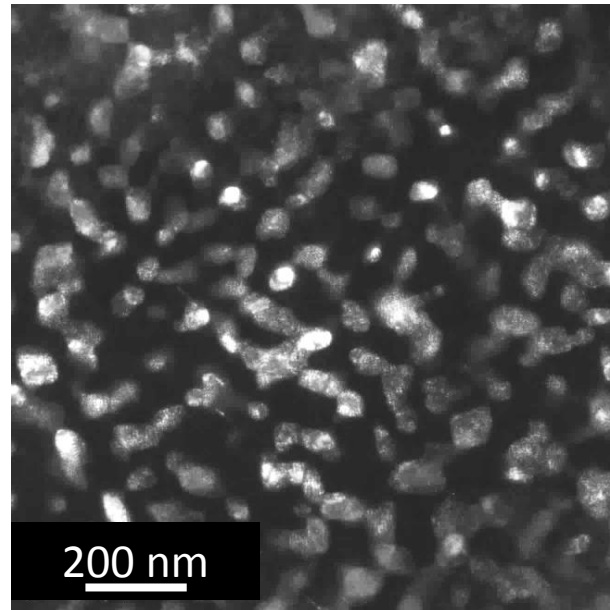
# Refractory CCA Superalloys (RSAs)

**Two-phase BCC+B2 alloys with atomically coherent, nanometer sized particles are similar to  $\gamma/\gamma'$  superalloy microstructures**

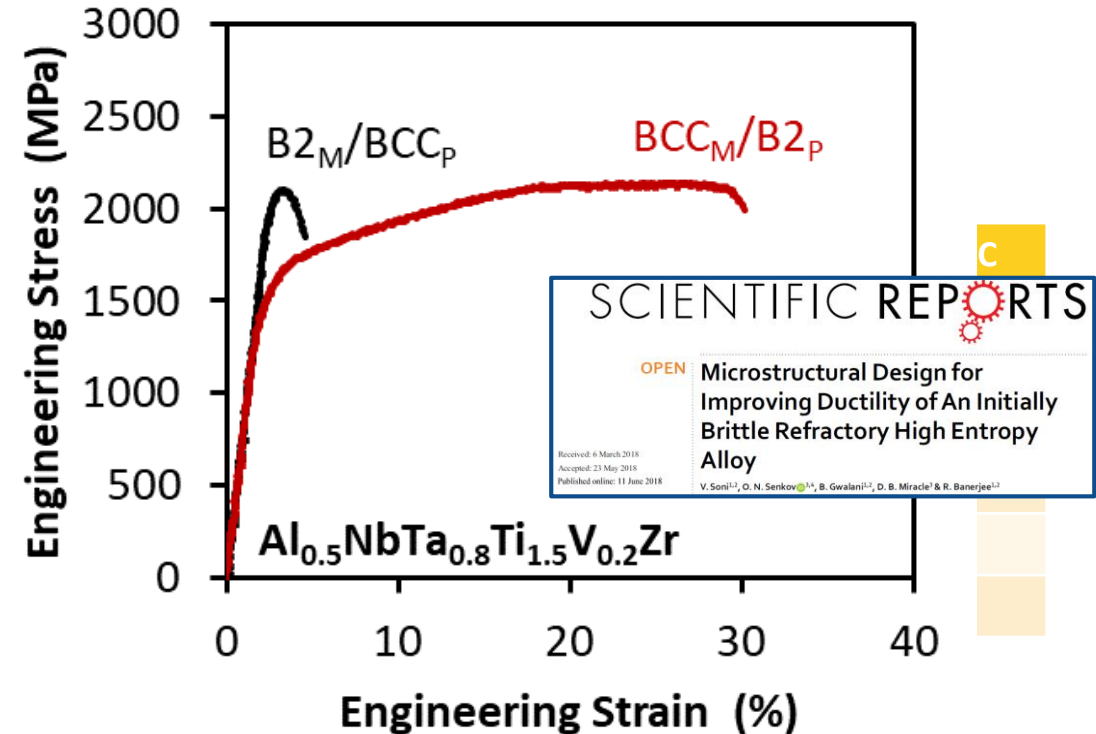
- B2 is typically the continuous phase but the microstructure can be inverted
- RSAs are among the highest strength RCCAs and also have improved oxidation resistance
- RSAs include  $\text{AlMo}_{0.5}\text{NbTa}_{0.5}\text{TiZr}$ ;  $\text{Al}_{0.3}\text{NbTaTi}_{1.4}\text{Zr}_{1.3}$ ;  $\text{Al}_{0.5}\text{NbTa}_{0.8}\text{Ti}_{1.5}\text{V}_{0.2}\text{Zr}$ ;  $\text{Al}_{0.5}\text{Mo}_{0.5}\text{NbTa}_{0.5}\text{TiZr}$



*B2 matrix + BCC cuboidal precipitates (brittle)*



*BCC matrix + B2 spherical precipitates (ductile)*



# High Entropy Ceramics

*Ordered compounds with ionic/covalent bonding*

**MPEAs are an alloying approach, not a family of alloys, so CCAs include other inorganic materials**

**The MPEA field includes ceramic materials such as oxides/ borides/ nitrides/ carbides**



nature  
COMMUNICATIONS

ARTICLE

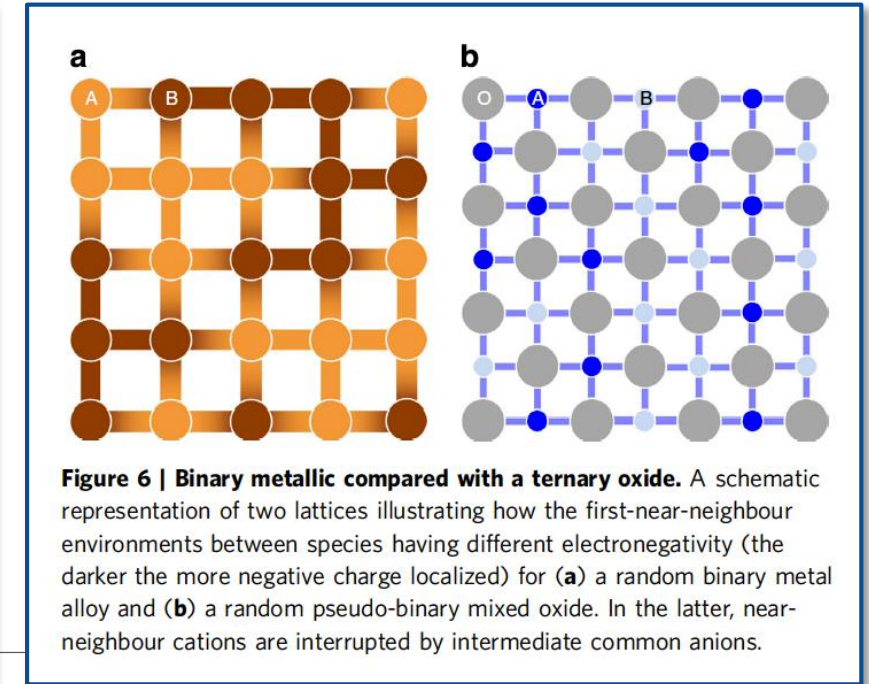
Received 8 Apr 2015 | Accepted 25 Aug 2015 | Published 29 Sep 2015

DOI: 10.1038/ncomms9485

OPEN

## Entropy-stabilized oxides

Christina M. Rost<sup>1</sup>, Edward Sachet<sup>1</sup>, Trent Borman<sup>1</sup>, Ali Moballegh<sup>1</sup>, Elizabeth C. Dickey<sup>1</sup>, Dong Hou<sup>1</sup>, Jacob L. Jones<sup>1</sup>, Stefano Curtarolo<sup>2</sup> & Jon-Paul Maria<sup>1</sup>



# Environmental resistance

## *Four degradation mechanisms*

### Solid solution interstitial hardening and embrittlement

- Rapid bulk diffusion produces thick, brittle surface layers in some refractory metals/alloys (alpha case in titanium alloys)

### Pest attack in some refractory metal aluminides, silicides

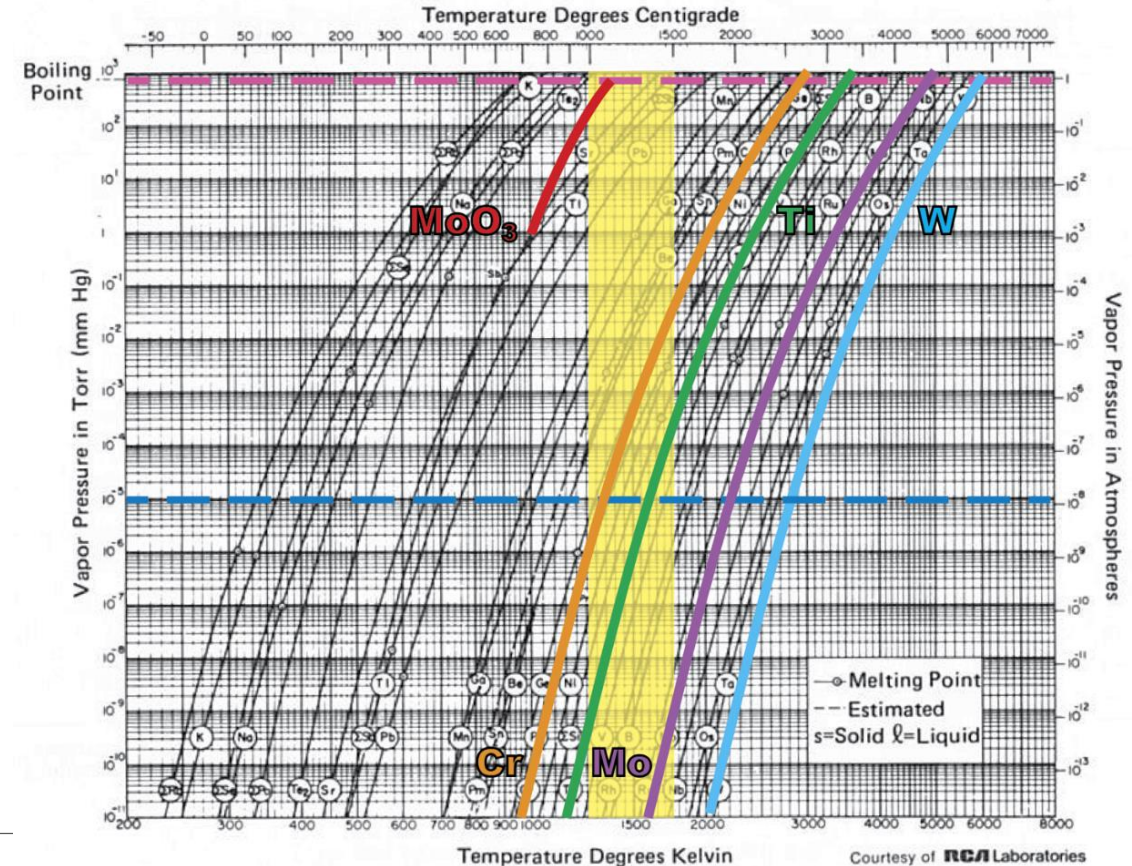
- Grain boundary oxidation near  $\sim 700^\circ\text{C}$  produces internal stresses that eject grains

### Volatilization

- Elemental Cr and  $\text{MoO}_3$  have high vapor pressures

### Rapid, non-protective oxide formation

- Includes internal oxidation

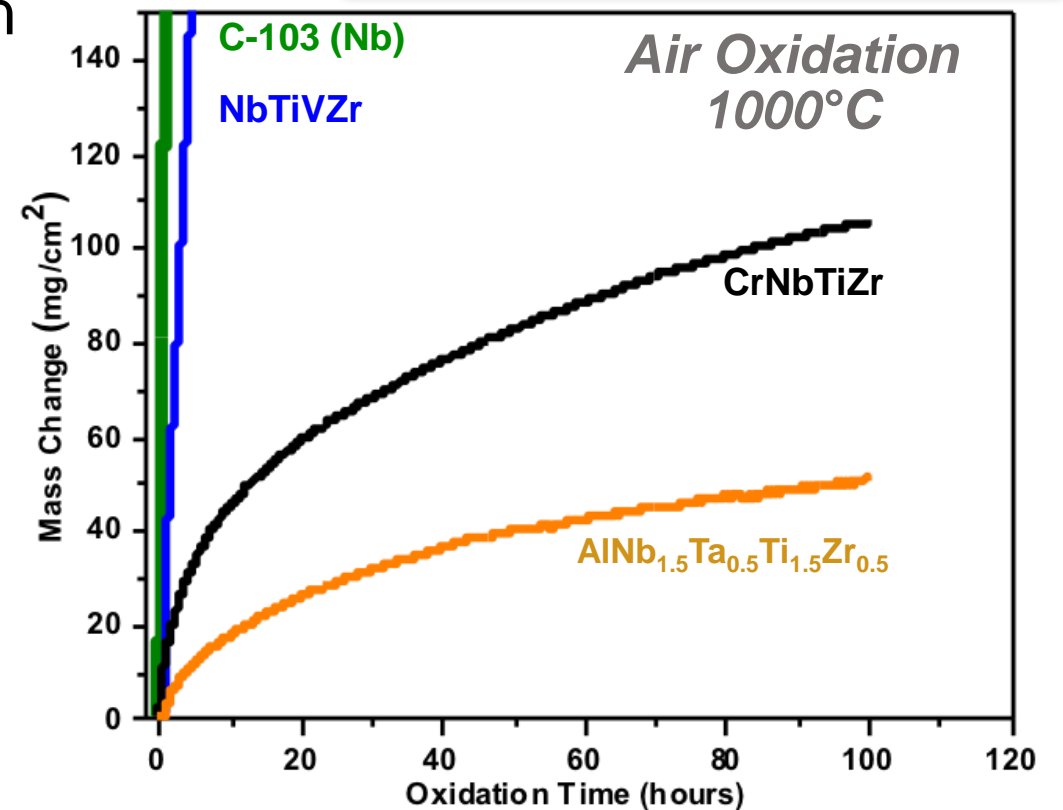
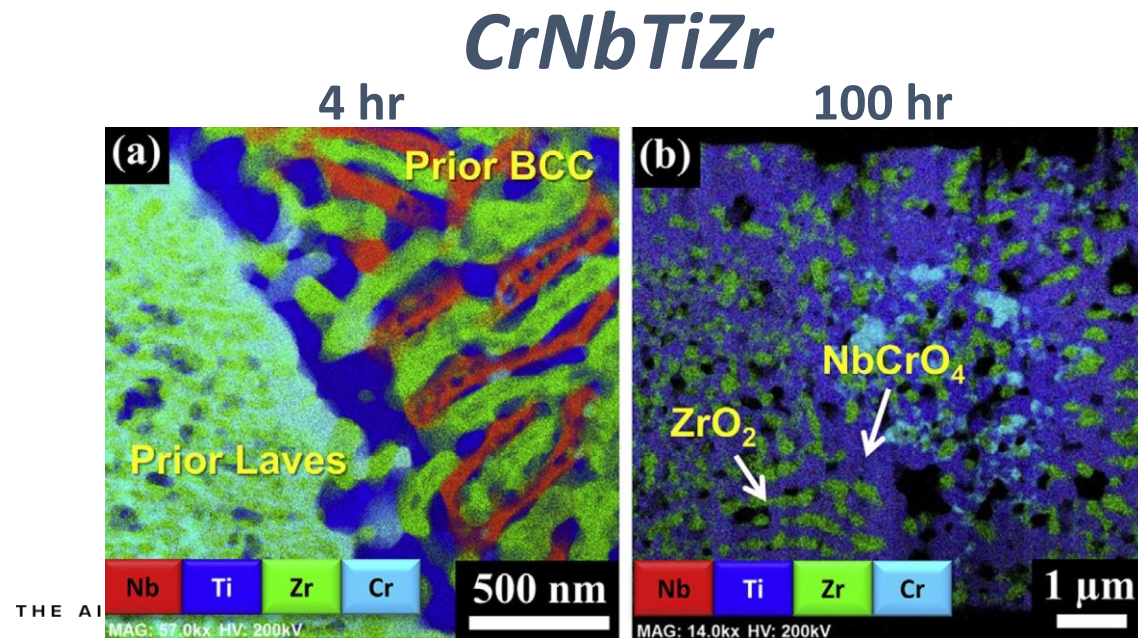


# Complex, concentrated alloys (CCAs)

*How are they different?*

## Exceptional oxidation resistance in refractory CCAs

- Parabolic kinetics that 100 times slower than conventional refractory alloys



# Brittle to ductile transition (BDT)

## *Competition between yield and fracture*

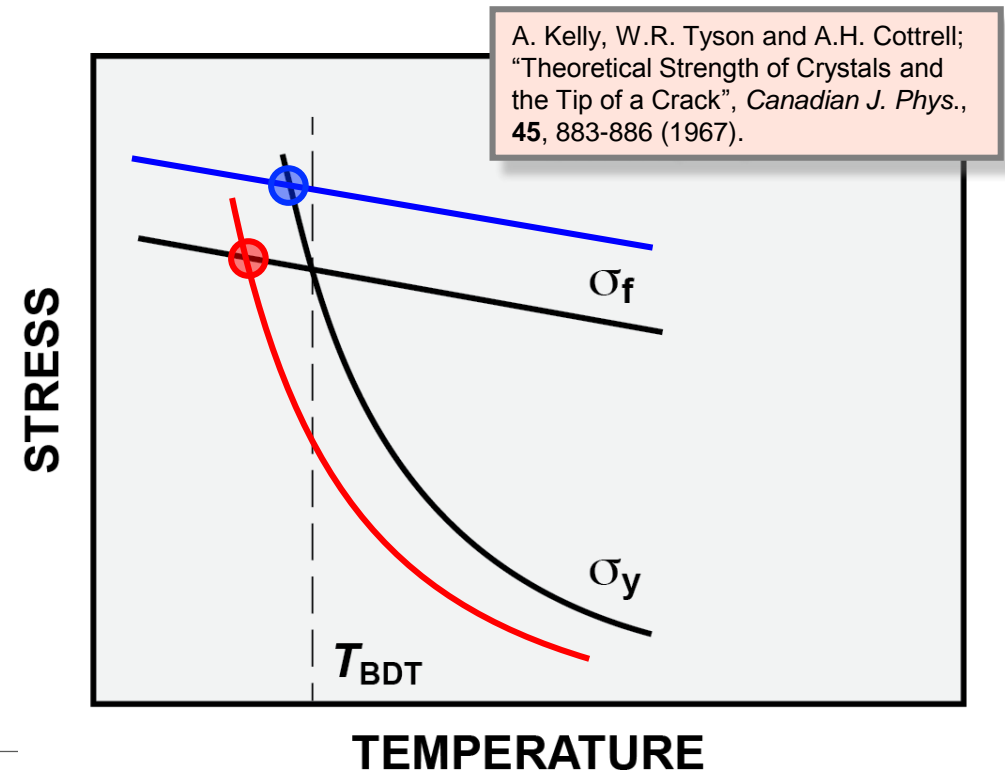
In BCC metals, fracture stress ( $\sigma_f$ ) is relatively insensitive to  $T$  but yield stress ( $\sigma_y$ ) depends strongly on  $T$

- A brittle-to-ductile transition temperature ( $T_{BDT}$ ) exists, below which fracture precedes bulk plastic deformation
- Increasing  $\sigma_f$  and decreasing  $\sigma_y$  decreases  $T_{BDT}$

**Other parameters also decrease  $T_{BDT}$**

- Increasing elastic modulus or surface energy
- Decreasing shear modulus or lattice constant
- Decreasing grain size

Designing RCCAs with these approaches may give  $T_{BDT} < RT$



# Large number of alloy systems


**CCAs offer a cosmically vast number of new alloy bases to explore**

**New strategies & tools can accelerate development by synergizing hi throughput computations & experiments**


- CALPHAD calculations can significantly accelerate exploration but thermodynamic databases for refractory elements need improvement
- High throughput experiments are needed, especially for environmental resistance and tensile ductility

CALPHAD: Computer Coupling of Phase Diagrams and Thermochemistry 50 (2015) 32–48

Contents lists available at [ScienceDirect](#)

 CALPHAD: Computer Coupling of Phase Diagrams and Thermochemistry

journal homepage: [www.elsevier.com/locate/calphad](http://www.elsevier.com/locate/calphad)

Accelerated exploration of multi-principal element alloys for structural applications 

O.N. Senkov<sup>\*</sup>, J.D. Miller, D.B. Miracle, C. Woodward

Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH 45433, USA

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Viewpoint Article 

New strategies and tests to accelerate discovery and development of multi-principal element structural alloys

Daniel Miracle<sup>a,\*</sup>, Bhaskar Majumdar<sup>b</sup>, Katelun Wertz<sup>a</sup>, Stéphane Gorsse<sup>c,d,e</sup>

# Simplification by palette selection

## Refractory CCAs (RCCAs)

Development and exploration of refractory high entropy alloys—A review

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Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson AFB, Ohio 45433, USA

Jean-Philippe Couznic  
Université Paris Est, ICMPE (UMR 7182) CNRS-UPEC, 2-8 rue Henri Dunant, F-94320, Thiais F-94320, France

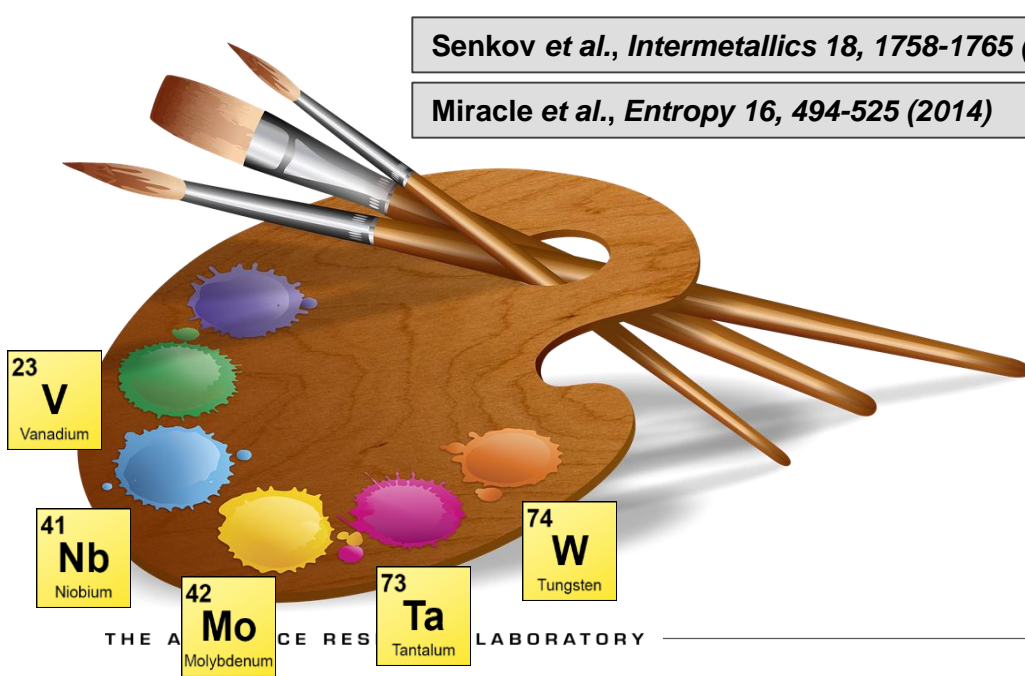
Refractory metals, conventional high temperature alloy elements (Co, Ni) and compound-forming elements (Al, Si, C, N...)

May also consider elements with high  $T_m$  and low cost, density (B, Fe, Y...)

This palette gives 'only' 43,605 bases with 3-6 principal elements

Senkov et al., *Intermetallics* 18, 1758-1765 (2010)

Miracle et al., *Entropy* 16, 494-525 (2014)



THE AIR FORCE RESEARCH LABORATORY

Periodic Table of the Elements

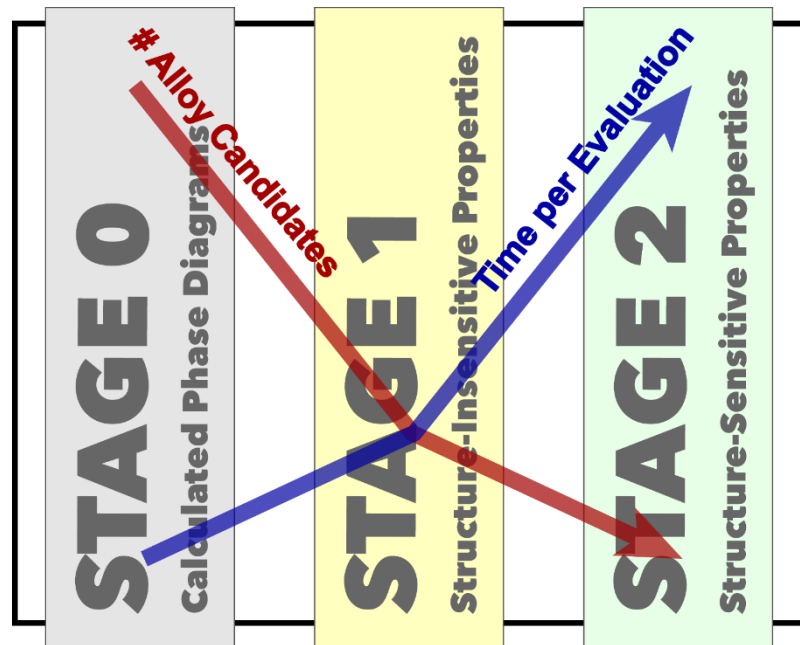
																		13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 1A H Hydrogen [1.00784;1.00811]			2 2A He Helium [4.002602]														5 3A B Boron [10.811;10.821]	6 4A C Carbon [12.0096;12.011]	7 5A N Nitrogen [14.00643;14.007]	8 6A O Oxygen [15.999;15.9997]	9 7A F Fluorine [18.998403;18.998]	10 8A Ne Neon [20.1797]	
3 Li Lithium [6.938;6.957]	4 Be Beryllium [9.012182;9.013]														13 Al Aluminum [26.9815386;27]	14 Si Silicon [28.0855;28.086]	15 P Phosphorus [30.973761998;31]	16 S Sulfur [32.059;32.076]	17 Cl Chlorine [35.446;35.457]	18 Ar Argon [39.948;41]			
11 Na Sodium [22.98976928;23]	12 Mg Magnesium [24.304;24.307]	3 3B Sc Scandium [44.9559085;45]	4 4B Ti Titanium [47.867;47.8671]	5 5B V Vanadium [50.9415;50.94151]	6 6B Cr Chromium [51.99616;52]	7 7B Mn Manganese [54.938045;55]	8 8 26 Fe Iron [55.845;55.845]	9 VIII 27 Co Cobalt [58.933194;59]	10 VIII 28 Ni Nickel [58.9334;58.9334]	11 IB 29 Cu Copper [63.546;63.5463]	12 IIB 30 Zn Zinc [65.38;65.382]	31 3A Ga Gallium [69.723;69.7231]	32 4A Ge Germanium [72.630;72.6305]	33 5A As Arsenic [74.921595;75]	34 6A Se Selenium [78.9718;78.9718]	35 7A Br Bromine [79.904;79.907]	36 8A Kr Krypton [83.798;84]						
19 K Potassium [39.0983;39.1]	20 Ca Calcium [40.078;40.0784]	21 Sc Scandium [44.9559085;45]	22 Ti Titanium [47.867;47.8671]	23 V Vanadium [50.9415;50.94151]	24 Cr Chromium [51.99616;52]	25 Mn Manganese [54.938045;55]	26 Fe Iron [55.845;55.845]	27 Co Cobalt [58.933194;59]	28 Ni Nickel [58.9334;58.9334]	29 Cu Copper [63.546;63.5463]	30 Zn Zinc [65.38;65.382]	31 Ga Gallium [69.723;69.7231]	32 Ge Germanium [72.630;72.6305]	33 As Arsenic [74.921595;75]	34 Se Selenium [78.9718;78.9718]	35 Br Bromine [79.904;79.907]	36 Kr Krypton [83.798;84]						
37 Rb Rubidium [85.4678;85.46783]	38 Sr Strontium [87.62;87.621]	39 Y Yttrium [88.90584;89]	40 Zr Zirconium [91.224;91.2242]	41 Nb Niobium [92.90638;92.90638]	42 Mo Molybdenum [95.94;95.94]	43 Tc Technetium [98]	44 Ru Ruthenium [101.07;101.072]	45 Rh Rhodium [102.90550;102.90550]	46 Pd Palladium [106.42;106.421]	47 Ag Silver [107.8682;107.8682]	48 Cd Cadmium [112.414;112.4144]	49 In Indium [114.818;114.8183]	50 Sn Tin [118.710;118.7107]	51 Sb Antimony [121.757;121.7571]	52 Te Tellurium [127.603;127.6033]	53 I Iodine [126.90447;126.904473]	54 Xe Xenon [131.29;131.2938]						
55 Cs Cesium [132.90545196;133]	56 Ba Barium [137.327;137.3271]	57-71 Lanthanide Series	72 Hf Hafnium [178.49;178.492]	73 Ta Tantalum [180.94788;180.94788]	74 W Tungsten [183.84;183.841]	75 Re Rhenium [186.207;186.2071]	76 Os Osmium [190.23;190.233]	77 Ir Iridium [192.222;192.222]	78 Pt Platinum [195.084;195.0849]	79 Au Gold [196.966569;196.9665695]	80 Hg Mercury [200.59;200.5923]	81 Tl Thallium [204.382;204.385]	82 Pb Lead [207.2;207.21]	83 Bi Bismuth [208.9804;208.980431]	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon [222]						
87 Fr Francium [223]	88 Ra Radium [226]	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [263]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [266]	110 Ds Darmstadtium [267]	111 Rg Roentgenium [268]	112 Cn Copernicium [269]	113 Uut Ununtrium [unknown]	114 Fl Flerovium [289]	115 Uup Ununpentium [unknown]	116 Lv Livermorium [289]	117 Uus Ununseptium [unknown]	118 Uuo Ununoctium [unknown]						
		57 La Lanthanum [138.90547;139]	58 Ce Cerium [140.12;140.124]	59 Pr Praseodymium [140.90766;140.907662]	60 Nd Neodymium [144.242;144.2423]	61 Pm Promethium [145]	62 Sm Samarium [150.36;150.362]	63 Eu Europium [151.964;151.96431]	64 Gd Gadolinium [157.25;157.253]	65 Tb Terbium [158.92532;158.925325]	66 Dy Dysprosium [162.50;162.5031]	67 Ho Holmium [164.93032;164.930325]	68 Er Erbium [167.259;167.2593]	69 Tm Thulium [168.934;168.934253]	70 Yb Ytterbium [173.054;173.0543]	71 Lu Lutetium [174.967;174.9671]							
		89 Ac Actinium [227]	90 Th Thorium [232.0375;232]	91 Pa Protactinium [231.03688;231]	92 U Uranium [238.02891;238]	93 Np Neptunium [237]	94 Pu Plutonium [244]	95 Am Americium [243]	96 Cm Curium [247]	97 Bk Berkelium [247]	98 Cf Californium [251]	99 Es Einsteinium [252]	100 Fm Fermium [257]	101 Md Mendelevium [258]	102 No Nobelium [259]	103 Lr Lawrencium [262]							



# New strategies are being proposed

Simplify by separating composition, microstructure evaluations

Evaluations that **reject the largest number of alloys with the smallest effort** are done first



## New Characterization Strategy

### Stage 0

-Hi throughput computations

### Stage 1

-Microstructure-insensitive properties  
 -Environmental resistance,  $T_m$   
 -Modulus, density, thermal properties

### Stage 2

-Microstructure-sensitive properties  
 -Tensile strength and ductility...

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Viewpoint Article

New strategies and tests to accelerate discovery and development of multi-principal element structural alloys

Daniel Miracle<sup>a,\*</sup>, Bhaskar Majumdar<sup>b</sup>, Katelun Wertz<sup>a</sup>, Stéphane Gorsse<sup>c,d,e</sup>

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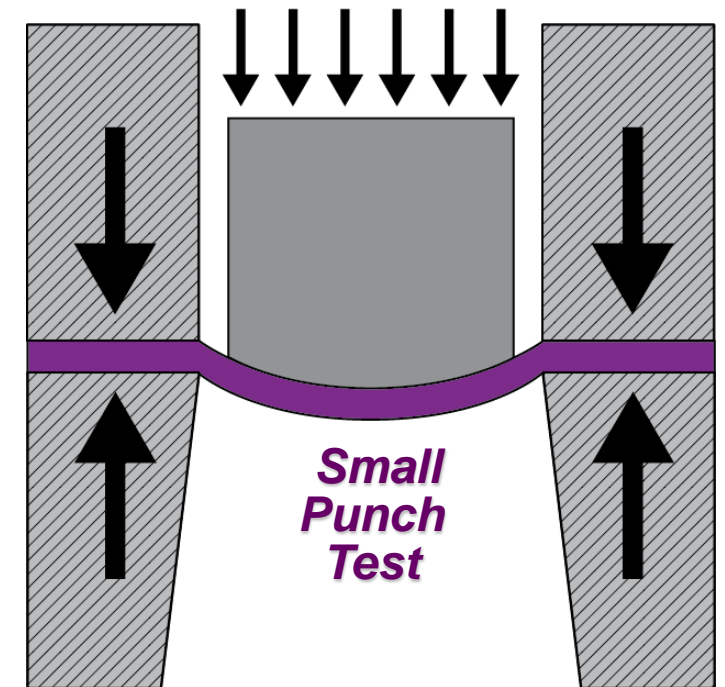
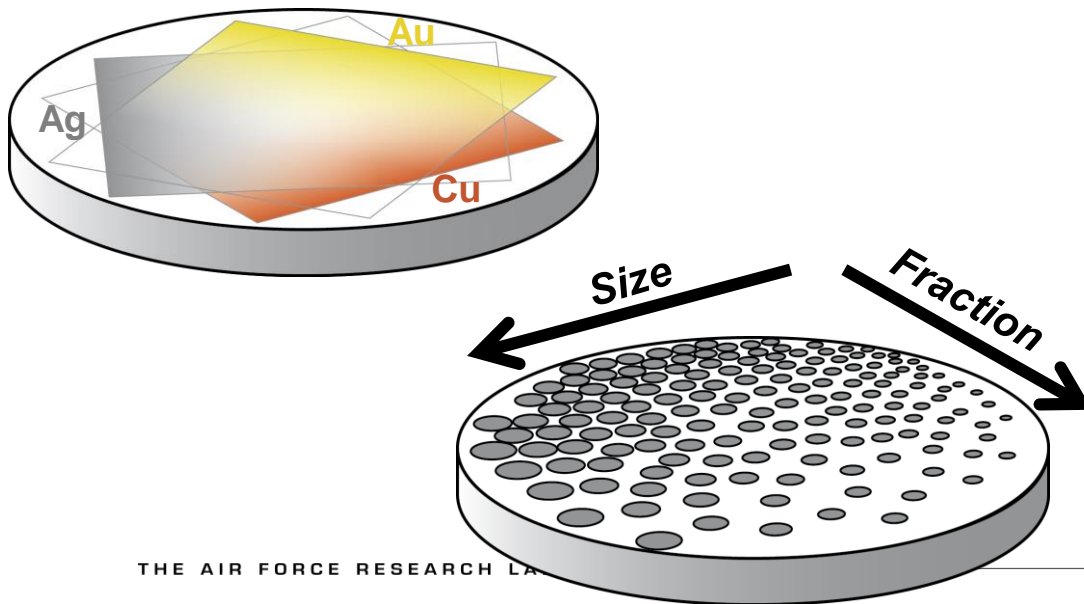
# High throughput experiments

**Don't exist for structural materials due to microstructure, length scale issues**

- Tensile properties and environmental resistance are top priorities

**New approaches for materials libraries are needed**

- Graded composition, **graded microstructure** and 'materials on demand' (candy dot)
- Bulk-like libraries (not thin films) for mechanical properties
- Emerging capabilities may make these feasible





# Back to the Future – *Fundamental data*

**Current scientific progress is built upon fundamental data and knowledge collected more than 50 years ago**

- Thermodynamic data and phase equilibria
- Phase transformations and phase stability
- Defects and defect energies (point, line, planar)
- Diffusion data and kinetic models
- Deformation mechanisms under different loading conditions
- *... and the influence of composition on the properties above!*

**These data typically describe alloys with a single dominant solvent**

**It has become difficult to fund research collecting fundamental data**

**The materials community must once again embrace the collection of fundamental data, especially in concentrated alloys**



# Back to the Future – *Materials screening*

**Materials screening used to be an important tool in materials research, but now...**

- Funding agencies view screening as applied work, or mere phenomenology
- Many researchers avoid screening due to lower accuracy than more time-consuming methods

**Screening allows researchers to quickly focus their efforts on materials that are most likely to have a significant impact on society!**

***We need to re-invigorate screening as an essential tool in basic science***

- Better targets R&D resources to develop the most impactful knowledge
- Current R&D methods have inherent risks that are usually ignored

**Imagine a 1 hour test with 100 questions...**

**Is it better to spend all your time on 1 question and be 99% sure of the answer...  
...or would you rather be 70% sure of your answers for all 100 questions?**

# Closing remarks

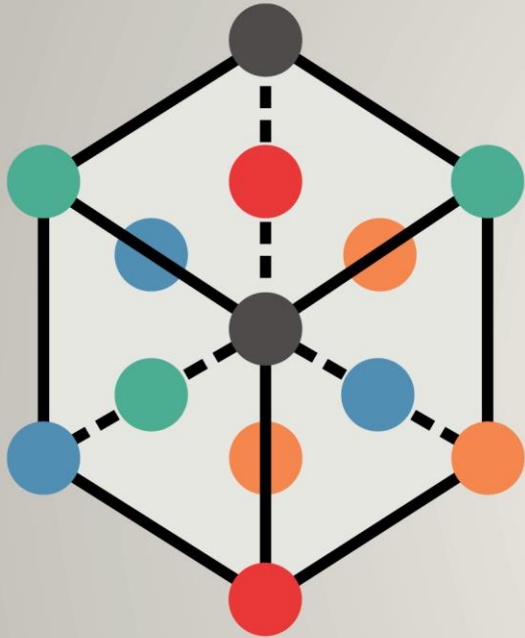
**HEAs/ CCAs change a 5,000 yr paradigm for developing materials**

**HEAs/ CCAs offer new challenges from vastness and new physical phenomena**

**Refractory CCAs offer significant promise but also three major technical challenges:**

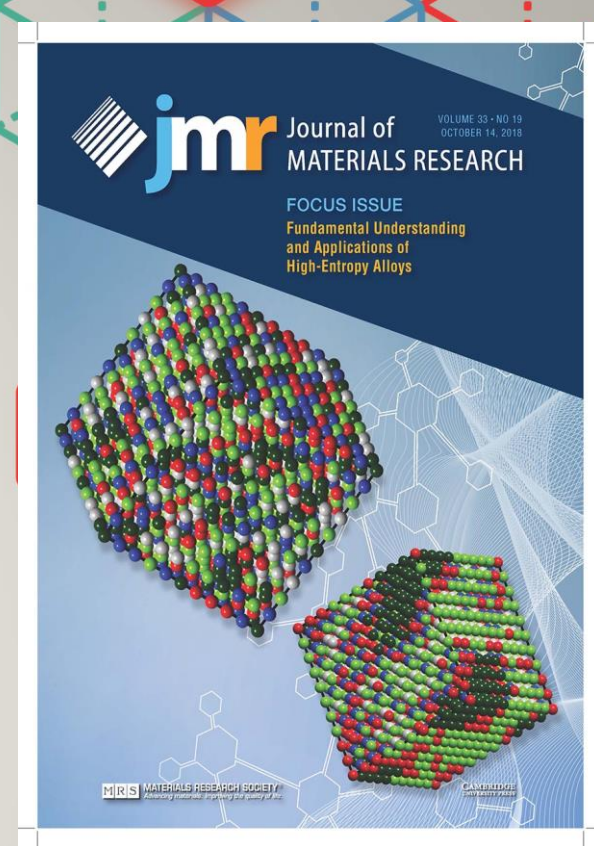
- environmental resistance (four distinct mechanisms)
- brittle-to-ductile transition (common to all BCC alloys)
- large number of new alloy bases to explore

**New high throughput strategies and tests are needed (*back to the future*)**



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# Questions?

